# APPLICATION OF ELECTROMAGNETIC FORCES IN CONTINUOUS CASTING MOLD: A REVIEW

Mohd Bilal Naim Shaikh[1], Maqusud Alam[2], Md Irfanul Haque Siddiqui[3]
[1,2,3] Department of Mechanical Engineering., Aligarh Muslim University, Aligarh, India
Email:bilalnaimshaikh@gmail.com[1], maqusudmce@gmail.com[2], irfansiddiqui.me@amu.ac.in[3]

**Abstract**

**Fluid flow characteristics in the mold region play a vital role in deciding the quality of steel produced. The flow pattern of molten metal is accountable for the surface defects, slag entrainment and other surface quality problems. So the mold flow pattern must be restrained to avoid excessive surface velocities, high surface waves, inclusion entrapments and many other problems. Operating conditions that control the mold flow problems include casting speed, submergence depth, nozzle and mold geometry, mold powder, gas injection and electromagnetic forces. The application of magnetic field is an attractive tool as it is noninterfering and can be adjusted during operation. This paper explores different researches presented by researchers in order to study the effect of magnetic field on different quality deciding parameters.**

**Index Terms: electromagnetic brake, EMBr, electromagnetic stirring, flow field, inclusions, magnetic field, slag.**

## I. INTRODUCTION

Fluid flow during steelmaking, steel refining and steel casting process is very meaningful to steel quality because it affects other decisive phenomena which include turbulent flow in the molten steel, the transport of bubbles and inclusions, multi-phase flow phenomena, chemical and transport interactions between the steel and the slag, the effect of heat transfer during these mixing, refining and solidification processes. transport of solute elements and segregation. Numerous work has been done in altering fluid flow pattern and flow characteristics in tundish to ensure good quality of steel[1-3].

Electromagnetic forces are an important means to control fluid flow in the mold, combined with other casting conditions, nozzle, and mold geometry [4]. Magnetic field strength offers an effective and an adjustable control parameter that can be varied in real time, and inherently lower turbulent fluctuations. Different magnetic field arrangements have been used to help control the steel flow in continuous casting[1]. Electromagnetic control systems are classified broadly into two types: 1) EMBr, which uses direct current to keep a constant Electro-Magnetic field that applies a braking force in proportion to the flow velocity; and 2) Moving-field control, which produces a time varying magnetic field to actively drive the flow, including accelerating, decelerating, or stirring action.

EMBr type systems include local, single-ruler, and double-ruler configurations. Local EMBr applies a circular shaped magnetic field to limited regions on both sides of the nozzle. This region exerts a force on the steel jet passing through it, which slows and deflects the jet. A "ruler-brake" extends the magnetic field region over the whole mold width. Using two such magnetic-field rulers is more well-known because it allows independent control of both surface velocity, and velocity in lower recirculation zone while avoiding direct interaction with the jet. Moving (traveling) magnetic-field systems can vary between many different modes, including electromagnetic level stabilizer (EMLS) to decelerate the flow, electromagnetic level accelerator (EMLA), electromagnetic stirring [rotational Mold-EMS / EMRS or final-strand-EMS].

Unfortunately, the complete interaction between melt flow, magnetic fields, turbulence, etc. may lead to damaging effects, e.g. an amplification of mold flow oscillation amplitudes. Hence the analysis of MHD mold flows is a very active field of research. This paper reviews studies to understand and optimize electromagnetics to control fluid flow in the mold in order to improve quality in continuous casting of steel.

## II. MODELING WITH ELECTROMAGNETIC EFFECTS

The first step in modelling flow in the mold with electromagnetic effects is to determine the external applied magnetic field, $B_0$, which can either be measured or calculated using the A-φ method given elsewhere [5]. Then, in addition to the flow model equations, coupled Maxwell's equations, and Ohm's law must be solved. The movement of the conducting steel through the applied magnetic field induces a current, which generates a Lorentz force that tends to oppose the flow.

Two different modelling approaches are used to model fluid flow with MHD, depending on the importance of coupling between the applied and induced magnetic fields.

When the Magnetic Reynolds number,

$$Re_m = \nu L(\mu\sigma)\ , < 1,$$

the induced magnetic field is negligible relative to the applied field, so the "electric potential method" is most efficient. Based on Ohm's law and conservation of charge, coupled equations for electric potential, $\phi$ , and Lorentz force, $\vec{F}_L$ can be solved as follows

$$\nabla^2\phi = \nabla\cdot\left(\vec{\nu}\times\overrightarrow{B_0}\right) \text{ and}$$

$$\vec{F}_L = \sigma\left(-\nabla\phi + \vec{\nu}\times\overrightarrow{B_0}\right)\times\overrightarrow{B_0} \tag{1}$$

In time varying fields, and when the induced current is significant, ($Re_m$ >1), the "magnetic induction" method is best.

Maxwell's equations are combined with Ohm's law to obtain a transport equation for the induced magnetic field, $\vec{b}$ in terms of the total field $\vec{B}$, and the current density $\vec{J}$.

$$\frac{\partial\vec{b}}{\partial t} + (\vec{\nu}.\nabla)\vec{b} = \frac{1}{\mu\sigma}\nabla^2\vec{b} + \left(\left(\overrightarrow{B_0} + \vec{b}\right).\nabla\right)\vec{\nu} - (\vec{\nu}.\nabla)\overrightarrow{B_0} - \frac{\partial\overrightarrow{B_0}}{\partial t} + \frac{1}{\mu\sigma}\nabla^2\overrightarrow{B_0} \tag{2}$$

$$\vec{B} = \overrightarrow{B_0} + \vec{b} \qquad \vec{J} = \nabla\times\frac{\vec{B}}{\mu} \qquad \overrightarrow{F_L} = \vec{J}\times\vec{B} \tag{3}$$

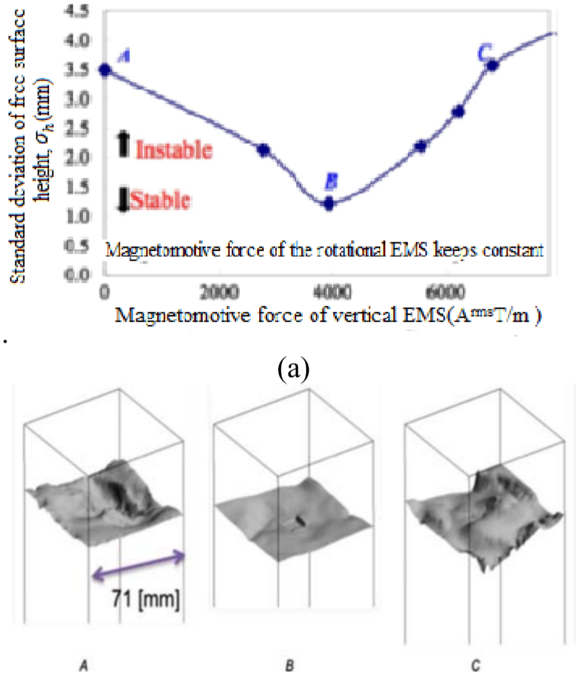
Here, $\sigma$ is the conductivity of the material, $\phi$ is the electric potential, and $\overrightarrow{B_0}$ is the applied magnetic field

In both methods, the Lorentz force is applied as a source term into the flow equations to alter the fluid velocities [6].

## III. LITERATURE REVIEW

In the last decades, the Electromagnetic Processing of Materials (EPM) has come forth as a branch of science and engineering concerned to the application of electromagnetic interactions for the processing of materials. Currently, there are prevalent industrial applications of EPM that use electromagnetic fields to control processes involving conductive fluids, such as liquid metals, molten salts or semiconductor materials. Although electromagnetic fields have been used in the material processing industry for many years, mainly for melting and refining metals or alloys, in the majority of applications the fundamental understanding of the involved phenomena was not present. After that more reasonable approaches of the non-intrusive action of electromagnetic fields were implemented to the handling, control, transport, and monitoring of electrically conducting liquids in miscellaneous industrial processes [9].

Ryo Otake and his fellows [10] investigate the effects of double-axis electromagnetic stirring (DAEMS) in continuous casting process, which is composed of a rotational electromagnetic stirrer and a vertical electromagnetic stirrer, using unsteady 3-D hydrodynamic calculation of the molten gallium model. Though in-mold electromagnetic stirring (M-EMS) is effective to prevent entrapment of non-metallic inclusions to solidified shell and to increase fine equiaxed structure but deformation of free surface caused by strong M-EMS promotes engulfment of mold powder to the molten steel. To resolve this issue, application of double-axis electromagnetic stirring (DAEMS) in continuous casting is investigated. To evaluate the free-surface stability, averaged standard deviation of the free surface is calculated. Fig. 1(a) shows the change in depending on the current in vertical EMS. Fig. 1(b) shows the free-surface shape at and in Fig. 1(a).



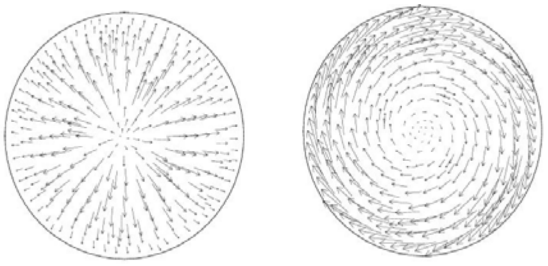
(a)

(b)

*Figure 1:(a) Free-surface stability, (b) Free-surface shape at A, B and C in (a) (Ref. [10]).*

From Fig. 1, it is found that there is an optimum vertical stirring intensity from the view of meniscus stability. From the calculation results, it is found that there is an optimum intensity balance between a vertical magnetic stirrer and a rotational magnetic in order to stabilize the free surface.

Yu Haiqi and Zhu Miaoyong [11] investigate numerically the flow characteristics of molten steel and inclusion trajectory in round billet mold using electromagnetic stirring (EMS). The calculation results show that EMS has an obvious effect on the flow and temperature distribution of molten steel, and the macrostructure of the billet. Lorentz force which creates a moment torque acting on the molten steel and leads to the stirring of the molten steel in the mold in the rotating direction. Without M-EMS, most of superheated molten steel directly flows downward, and only a little molten steel flows to the top surface of the mold to form a pair of recirculation zones. in the mold as shown in Fig. 5(a). With MEMS, formed rotating electromagnetic force leads the flow field of molten steel in the mold to form two pairs of recirculation zones, and the temperature distribution of molten steel in the mold is more uniform and the recirculating direction of the molten steel is from the mold wall flowing to the center of the mold at the lower region of the mold as shown in Fig. 2(b).Without M-EMS and with M-EMS, the velocity and temperature distributions at the center symmetry plane of the mold are shown in Fig. 2 & 3.



*(a)* *(b)*

*Figure 1: Velocity distributions at the horizontal section of the mold. (a) Without M-EMS, (b) With M-EMS. (Ref. [11])*

The rotating electromagnetic force is formed, that leads to the flow field of molten steel in the mold forms two pairs of recirculation zones, and the temperature distribution of molten steel in the mold is more uniform. Moreover, the floating up rate of inclusions is increased with M-EMS. This means that it is useful to improve the metallurgical quality of billet by the M-EMS system.

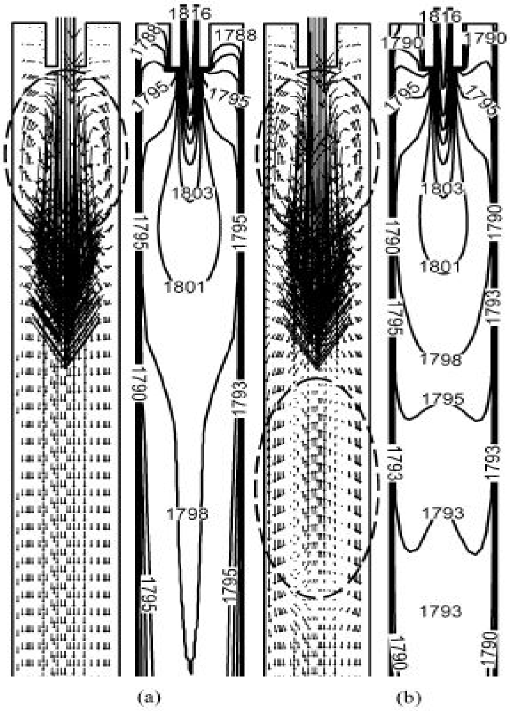
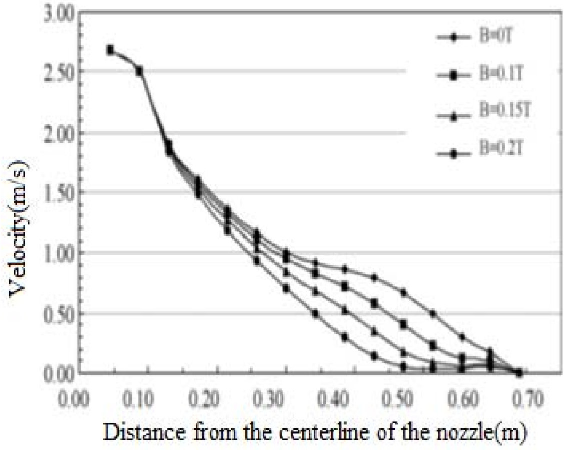
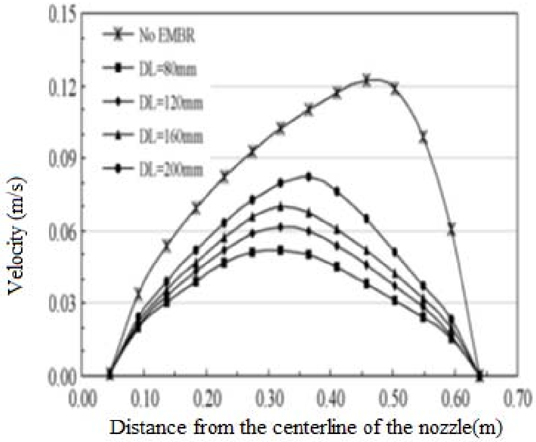


*Figure 2: Velocity and temperature distributions in the mold. recirculation zones are emphasized by ellipse dash line. (a) Without M-EMS. (b) With M-EMS (Ref. [11]).*

Yu Haiqi, Wang Baofeng, Li Huiqin and Li Jiancha [12] shows that flow field in the mold can be effectively controlled by electromagnetic brake; electromagnetic force is the motive power of braking, the effects of EMBR is associated directly with the intensity magnitude of magnetic field, the reciprocal position between magnetic field and acting region and casting speed. Casting speed has the most significant influence on the liquid steel flow state in mold and the quality of products, especially under high casting speed [13]. EMBR may effectively suppress the flow velocity of liquid steel in mold under high casting speed, improve the liquid steel flow state and eliminate the negative phenomena. Thus it establishes the foundation to increase casting speed. The magnetic induction intensity and the position of brake region will affect the braking effect. The braking effect becomes more significant as the external magnetic field intensity increases, the re-circulating flow velocity and impinging intensity become weak, the re-circulation zones gradually become shallow. The braking position seriously affects the flow field. This paper provides a reference for actual production to discover the reasonable magnetic field intensity, the braking position and design reasonable electromagnetic brake installation. Fig. 4(a) shows the flow velocity of the liquid steel mainstream is obviously suppressed along with the increase of magnetic induction intensity, the flow velocity decreased gradually down the way.



(a)



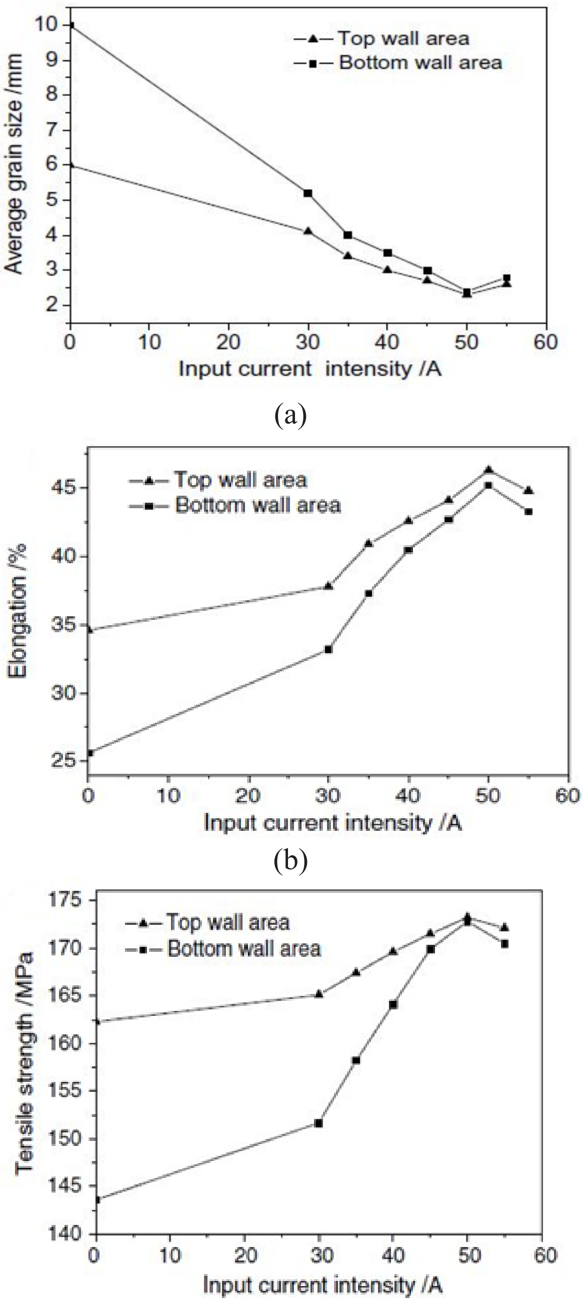
(b)

*Figure 3: (a) Variations of the liquid steel mainstream velocity along x direction for the different intensity of magnetic induction (b) Variations of velocity under the free surface along x direction for the different location of EMBR (Ref. [12]).*

It is seen that the braking effect works efficient significantly by gradually increasing the magnetic induction intensity. In conclusion, the flow velocity of liquid steel in the mold can be reduced gradually while the magnetic induction intensity increases. It can be seen from Fig. 4(b), the suppression effect on the flow velocity of the free sur- face is weakened significantly while the magnetic field region moves down the free surface gradually

Yufeng Wang, Anping Dong, and Lifeng Zhang [14] investigate the effect of electromagnetic brake (EMBr) on fluid flow and particle motion in steel slab continuous casting strands. The application of EMBr would be a remedy to the swirl flow in the casting mold. Flow pattern has great influence on the trajectories of injected bubbles and non-metallic inclusions. More bubbles tend to release from the top surface near the wide face opposite to the gate opening side without EMBr; while, they escape at the center place of the slab thickness when the EMBr was applied. During the continuous casting, molten steel enters the casting mold through a SEN. The flow rate of the molten steel is commonly controlled by either slide gate or stopper rod. The off-center slide gate may generate an asymmetric or biased flow in the nozzle and thus in the mold. The asymmetric flow inside the casting mold always induces a lower steel quality. the slide orientation has great influence on the flow pattern and characteristic of the jet exiting the nozzle out ports with 0 gate orientation generates the worst biased flow. For the current study, a local brake type EMBr was employed with a 0.39T magnetic field. The effect of EMBr on the fluid flow in the mold without slide gate and in the mold with a 50% opening slide gate were studied and compared. The results indicate that EMBr has little effects on the jet characteristics at SEN out ports. However, EMBr has great impact on the fluid flow inside the mold. EMBr could provide Lorenz force to brake the jet coming from SEN out ports. EMBr has little effect on the overall removal fraction of inclusions, while it affects the distribution of inclusions in the slab. With EMBr, the cleanliness in the slab centre can be improved.

Yan Zhiming , Liu Hui & Li Tingju [15] used alternating magnetic field of commercial frequency during horizontal continuous casting of copper hollow billets. Author’s group applied a soft-contact electromagnetic field of commercial frequency and median frequency during horizontal continuous casting of copper alloy hollow billets and studied the effect of the rotating electromagnetic field intensity on solidification structure, surface quality and mechanical properties of copper alloy hollow billets which obtained prominent progress. The alternating magnetic field can refine the solidification structure of copper hollow billets whose solidification structure turns from inhomogeneous columnar grains to homogeneous equiaxed grains. The variations of casting parameters such as casting speed, casting temperature and cooling intensity have greatly effects on the action of alternating magnetic field [16]. When an alternating magnetic field is imposed from outside of graphite inner-mold, the forced flow induced by electromagnetic body force generates shearing force in melt, which acts on the root of the grains on the wall of graphite inner-mold and compels the grains to dissociate. The grains are suffered from temperature fluctuation, which leads to the process of growth-remelt-growth. The large grains are fused into lots of small grains, so the grains multiply quickly.



(a)

(b)

(c)

*Figure 4: Effect of input current intensity on mechanical properties of copper hollow billets:(a) Average grain size (b) elongation and (c) tensile strength (Ref. [15]).*

Turbulent flow when steel is delivered through a nozzle in a slab mold induces dragging forces at the metal–slag interface that entrain slag droplets into the metal bulk[17]. These dragging effects are discontinuous and correspond to the velocity fluctuations of turbulence at that interface which themselves, are dependent on nozzle immersion, nozzle design, mold width and casting speed. Slag viscosity and density, metal viscosity and slag layer thickness are employed to estimate that critical velocity which is embodied in a critical capillary number for some established mold operating conditions. This approach permits the link between all operating variables including flux chemistry and nozzle design with the interface instability. A relationship between the capillary number and the magnetic field strength used to brake the liquid steel is established which is used to assure the interface stability for any operating condition and flux chemistry. The braking effects were simulated using the mathematical model using the LES approach assuming liquid steel with the nozzle at the deep position. As expected, the velocity magnitudes decrease as the field strength gets larger and the dual nature of the jet is not modified since the magnets are located just below the ports. Nevertheless, Velocities at the meniscus level decrease as a consequence of the braking effect. The most interesting aspect is the effect of the EMBr on the generation of velocity spikes. The number of spikes decreases with the magnitude of the field strength.

## IV. PROPOSED PLAN WORK

Many researchers have been addressed the different techniques and arrangements of implication magnetic field for improvement in the quality of product. Mold geometry as well as magnetic field application are design on the basis of numerical and computational modelling method. The improvement in flow of mold is an important in continuous casting, and for overcoming slag inclusion beside of turbulence. The computational fluid analysis under magnetic forces is also proposed to carry out with optimize geometrical design and flow control devices.

## V. CONCLUSION

This research discussed about the different literature based on the computational modelling of mold under magnetic field. From the above researches and studies, we can conclude that fluid flow pattern can be control as directed according to required structure by applying electromagnetic forces with different intensity, different location and about different axis. It prevents excessive surface velocities and the corresponding slag entrainment, level fluctuations, inclusions, and surface defects that accompany casting without electromagnetics for corresponding geometry and casting speed. This paper summarizes different approaches to alter the flow pattern in the steel continuous casting mold using electromagnetic forces, and the computational methods used to study them. Computational models always require rigorous validation with plant measurements before extending their predictions to meaningful parametric studies [12-13]. Subsequent work is needed to investigate and quantify the stabilizing effect, application of magnetic forces in nozzle region.

In general, application of magneto hydrodynamic techniques greatly changes the volumetric flow pattern in the mold and deeper strand pool, and remarkably impacts the microstructural morphology, segregation, soundness, clean- lines and even properties of the cast products. Geometric constraint directly controls the fluid boundary and injecting guidance in the upper mold and sensibly influences surface quality, even subsurface quality, and cleanliness.

## VI. REFERENCES

[1]. I. H. Siddiqui and P. K. Jha, “Assessment of Turbulence Models for Prediction of Intermixed Amount with Free Surface Variation Using Coupled Level-Set Volume of Fluid Method,” vol. 54, no. 11, pp. 2578–2587, 2014.

[2]. I. H. Siddiqui and P. K. Jha, “Numerical Simulation of Flow - Induced Wall Shear Stresses in Three Different Shapes of Multi - Strand Steelmaking Tundishes,” vol. 85, no. 9999, pp. 1–9, 2014.

[3]. I. H. Siddiqui and P. K. Jha, “Effect of Inflow Rate Variation on Intermixing in a Steelmaking Tundish during Ladle Change-Over,”

[4]. K. Fujisaki, “In-Mold Electromagnetic Stirring in Continuous Casting,” vol. 37, no. 4, pp. 1098–1104, 2001.

[5]. B. G. Thomas and R. Chaudhary, “State of the Art in Electromagnetic Flow Control in Continuous Casting of Steel Slabs : Modeling and Plant Validation,” vol. 1, no. c, pp. 19–24, 2009.

[6]. Ryu Hirayama, Keisuke Fujisaki and Takahiro Yamada: IEEE Trans. Magn., vol. 40, no. 4, 2004 .

[7]. S. Mazumdar and S. K. Ray, “Solidification control in continuous casting of steel,” vol. 26, no. April, pp. 179–198, 2001.

[8]. P. Väyrynen, S. Wang, S. Louhenkilpi, and L. Holappa, “Modeling and Removal of Inclusions in Continuous Casting,” pp. 1132–1143, 2009.

[9]. B. G. Thomas, "Modeling of the continuous casting of steel - past, present and future," pp. 3–30, 2001.

[10]. R. Otake, T. Yamada, R. Hirayama, K. Fujisaki, S. Shimasaki, and S. Taniguchi, "Effects of Double-Axis Electromagnetic Stirring in Continuous Casting," vol. 44, no. 11, pp. 4517–4520, 2008.

[11]. E. Field, "Three-Dimensional Magnetohydrodynamic Calculation for Coupling Multiphase Flow in Round Billet Continuous Casting," vol. 46, no. 1, pp. 82–86, 2010.

[12]. Y. Haiqi, W. Baofeng, L. Huiqin, and L. Jianchao, "Influence of electromagnetic brake on flow field of liquid steel in the slab continuous casting mold," vol. 2, pp. 179–187, 2007.

[13]. R. Moreau. Magnetohydrodynamics. Kluwer Academic Publishers, 1990.

[14]. Y. Wang, A. Dong, and L. Zhang, "Effect of Slide Gate and EMBr on the Transport of Inclusions and Bubbles in Slab Continuous Casting Strands," vol. 82, no. 4, pp. 30–32, 2011.

[15]. Y. Zhiming, L. Hui, L. Tingju, Z. Xiaoqing, C. Zhiqiang, and Z. Xiaoli, "Effects of alternating magnetic field and casting parameters on solidification structure and mechanical properties of copper hollow billets," *Mater. Des.*, vol. 30, no. 4, pp. 1245–1250, 2009.

[16]. T. D. Canonsburg, "ANSYS FLUENT Tutorial Guide," vol. 15317, no. November, pp. 724–746, 2010.

[17]. R. D. Morales, "Control of Slag-Dragging Effects at the Metal – Slag Interface through Electromagnetic Brake in a Slab Mold," pp. 1–12, 2015.